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APPLICATION FOR UNITED STATES LETTERS PATENT

for

ELECTRICAL FAULT DETECTION SYSTEM

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ELECTRICAL FAULT DETECTION SYSTEM

CROSS-REFERENCE TO RELATED APPLICATION

[0001]   This invention claims the priority of U.S. Provisional Patent Application Serial

No. 60/428,537, filed November 22, 2002, for "ELECTRICAL FAULT DETECTION

SYSTEM."(Attorney Docket No.

FIELD OF THE INVENTION

[0002]   The present invention relates to the detection of ground-fault and ground-neutral

conditions using a microcontroller-based system.

BACKGROUND OF THE INVENTION

[0003]   The present invention provides a microcontroller-based system for detecting

ground-fault and grounded-neutral conditions in a monitored circuit of an electrical power

distribution system having both line and neutral conductors. The system includes a sensor

producing an output signal responsive to current flow in both the line and neutral conductors of

the monitored circuit. The system also includes a microcontroller for receiving and evaluating

the sensor output signal and initiating a circuit status signal indicating whether the monitored

circuit is operating normally, has a ground-fault condition or a grounded-neutral condition. The

microcontroller analyzes the sensor output signal with respect to predetermined or calculated

parameters to determine if a ground-fault condition is present in the monitored circuit. At

selected intervals the microcontroller initiates a pulse, referred to herein as a ping, in a resonant

circuit of the sensor and analyzes the sensor's response to the ping to determine if a grounded

neutral condition exists in the monitored circuit.

BRIEF DESCRIPTION OF THE DRAWINGS

[0004]   In the drawings:

[0005]   FIG. 1 is a functional block diagram of an electrical fault detection system

embodying the invention;

[0006]   FIG. 2 illustrates the waveform obtained from the ping signal with no fault (FIG.

2a), a fault of about 3 ohms (FIG. 2b) and a shorted fault at 0.5 ohms (FIG. 2c);

[0007]   FIG. 3 is a schematic diagram of an electrical circuit for implementing the arc fault detection system illustrated in FIG. 1; and

[0008]   FIGS. 4-9 are flow charts of a program executed by the microcontroller in the electrical circuit of FIG. 3.

DETAILED DESCRIPTION OF THE ILLUSTRATED EMBODIMENT

[0009]   Referring now to the drawings and initially to FIG. 1, there is shown a block diagram of one embodiment of an electrical fault detector system for detecting the occurrence of ground faults and grounded-neutral faults in an electrical circuit. This detector system includes a microcontroller 10 that uses an input signal received from a sensor 11, such as a current transformer, to determine whether a ground fault or grounded-neutral fault has occurred in the circuit being monitored, e.g., the functions required in UL 943. The sensor 11 is coupled to line and neutral conductors of the circuit being monitored for faults. When no fault conditions exist, there is no differential output signal from the sensor 11 because essentially the same current flows through both the line and neutral conductors, but in opposite directions. When a ground fault exists, a leakage path exists between the line conductor and ground, and the resulting current imbalance in the line and neutral conductors produces a differential output signal from the sensor 11. In some applications the sensor output signal may require amplification, filtering or further conditioning prior to being evaluated by the microcontroller 10 and is passed through a gain block 12, which can be a conventional operational amplifier. The microcontroller 10 analyzes the sensor output signal with respect to predetermined or calculated parameters to determine if a ground-fault or grounded-neutral condition is present in the monitored circuit and produces a circuit status signal indicating the circuit condition. A responding device 13 receives the circuit status signal and produces an appropriate output. Alternative embodiments could include an ASIC or other programmable chip device for the microcontroller 10 function. The measured signal or the output decision could be time averaged to improve noise resistance.

[00010]   Grounded neutral detection can be performed in many ways. The underlying goal of the algorithms discussed herein is to estimate the value of the resistance of the neutral-to-ground connection. In reference to FIG. 2, this resistance is the dominating factor in the change of the decay rate of the resonant oscillation formed as a result of the ping signal. Another factor that affects the oscillation decay is the internal resistance of the sensor 11. FIG. 2a shows the

resonant oscillation at about 9 ohms or no short present. FIG. 2b shows the effect of a fault at about 3 ohms. FIG. 2c shows a grounded fault condition at about 0.5 ohms. The rapid decay of the ping oscillation in the presence of fault conditions is clearly shown.

[00011] The aforementioned ping resonant oscillation can be expressed in the form of an exponential multiplied by a sinusoid as follows:

[00012] $A \sin (\omega\tau) \times e^{-\alpha t}$

[00013] 'A' represents the initial amplitude of the sinusoid, ω represents the frequency of oscillation, τ represents time, α is the decay factor. This α is the combination of the elements that cause the oscillation to decay. The neutral to ground resistance is directly related to this α. As the neutral to ground resistance goes down, α increases, causing the decay to be faster. In order to determine the presence of a predetermined value of neutral-to-ground resistance, this α parameter can be calculated or estimated by a number of methods. Each method offers benefits and compromises in terms of processing requirements and susceptibility to noise. Once estimated, the estimate may be compared to a setpoint for detection of a grounded-neutral fault. Each of the following methods can be implemented with only the positive, negative or both or absolute value of the oscillation cycles. These methods are described below:

[00014] Method 1: Envelope of Peaks – Observing that the form of the expression that describes the decaying oscillation contains a sinusoid and an exponential function, this method seeks to find the envelope exponential function. The peaks of the oscillation are located by any of a number of known methods. These peak values are used to create a model of the exponential function that envelopes the oscillation. A tangential function is used to determine the α value and used as the decision parameter.

[00015] Method 2: Polynomial Envelope of Peaks – This method is like Method 1 but uses a second order estimate of the function in the form $y = Ax^2 + Bx + C$. A is used to estimate α. A multi-order polynomial could also be used.

[00016] Method 3: Linear Envelope Estimate – This method is also like Method 1 except a linear fit of the peak values is found. The resulting slope of the best fit line is used to estimate α.

[00017]   Method 4: Area of Cycles – This method is like Method 1 but uses an estimate of the area below the signal waveform instead of peak values. The resulting points are fit to a model. A parameter of this model is used to estimate α. This method could use an exponential, linear or polynomial model as in Methods 1, 2 and 3.

[00018]   Method 5: Slope of Half Cycle – This method estimates the slope of the leading or tailing edge of a half cycle by measuring two or more points. The parameter to base decisions could be the slope of half cycle N where N is 1, 2, 3, 4....

[00019]   Method 6: Function of Slope of Half Cycles – This method requires calculation of the slope of M half cycles and then use of a parameter such as the slope of the resulting M half cycle slopes.

[00020]   Method 7: Threshold on the Slope of Half Cycles – This method requires calculation of the slope of M half cycles and then use of a threshold to count the number of half cycles above a preselected threshold. The number of half cycles with a slope above the threshold is used as the decision parameter. This method will be described in more detail below with reference to FIGs. 4-9.

[00021]   Method 8: Count Peaks Above a Threshold – A fixed number of half cycles or a fixed timer period is monitored. During this time, the number of half cycles that cross above a preselected threshold is counted. A decision parameter based on the number of peaks above the threshold is used.

[00022]   Figure 3 is a circuit diagram of a fault detection system constructed in accordance with the present invention. The microcontroller 10 is a typical device such as the PIC12C672 microcontroller, which has an internal timer, an internal analog-to-digital (A/D) converter, and analog and digital ports, or a digital signal processor or ASIC with similar features. The sensor 11 can be as simple as a current transformer or include other components as required to enhance its operation. The sensor 11 is configured such that both the line and neutral conductors of the monitored circuit constitute the primary winding. The A/D converter built into the microcontroller 10 converts the analog sensor output signal to a corresponding digital signal.

[00023]   In the illustrative example, the fault detection system responds to a fault condition by producing a circuit status signal that is supplied to a responding device 13, such as

the LED shown, which indicates the circuit status signal. It is to be understood that the responding device **13** can be any device capable of producing a desired response to the circuit status signal. The microcontroller **10** continually compares the magnitude of the sensor output signal with a stored threshold value to determine whether a ground fault has occurred. The microcontroller **10** also produces a ping signal that is supplied to the sensor **11** at selected intervals to produce a response in the sensor output signal that can be analyzed to determine whether a grounded-neutral fault has occurred. When either a ground fault or a grounded neutral is detected, the microcontroller **10** produces a circuit status signal indicating a fault condition in the monitored circuit.

[00024] The microcontroller **10** is controlled by a program stored in memory built into the microcontroller **10**. The operations carried out by the program are illustrated by the flow charts in FIGs. 4-9. Specifically, FIG. 4 represents the initializing sequence, FIG. 5 represents a main loop of the program, and FIGS. 6-9 represent four state routines that are executed selectively during iterations of the main loop. It should be noted that, while only one of the four state routines is active during each pass of the main loop, as determined by the variable **currentState** in the illustrated example, it is within the scope of the invention for the microcontroller **10** to process all four states during each pass of the main loop.

[00025] The routine of FIG. 4 begins upon power-up as depicted at step **100**. At step **102** the microcontroller **10** initializes its various ports and system variables. At step **104** the variables **currentState** and **nextState** are initialized to the **WaitForZeroMinusState**. At step **106** an internal real-time counter is initialized to interrupt at a fixed interval that determines the rate at which the signal from the sensor **11** is sampled. At step **108** the microcontroller program executes the main loop until the machine is reset or power is discontinued.

[00026] Figure 5 illustrates the program actions common to all main loop sequences. At step **120** the real time counter initialized in step **106**, is loaded with a preset value, which starts the fixed sample interval. At step **122** the microcontroller **10** samples the sensor output signal (a voltage sample). This sample is used for tests and comparisons during this loop. At step **123** a **waitFlag** is set. At step **124**, one of the four state routines is called based on the **currentState** variable. The four state routines will be described in detail below, including those that determine whether a ground-fault or grounded-neutral fault has occurred, in which case a corresponding fault indicator is set. The **MeasuredNegCycleState** represents one method for determining a ground-fault condition and the **MeasuredN2GndState** represents one method for

determining a neutral-to-ground fault condition. Method 8 for determining a neutral-to-ground fault condition as described above has been selected for the purpose of illustrating one operating embodiment of the electrical fault detection system of the present invention. After completing the **currentState** routine, the **currentState** variable is set to the **nextState** value at step **137**. Checks are then made at steps **138** and **140** to determine if either the ground fault or the neutral-to-ground fault indicator is set. If either fault indicator is set, then control is passed to step **144** where a fault indicator output is updated to reflect a fault status in the monitored circuit. If neither fault indicator is set, then control is passed to step **142** where the fault indicator output is updated to reflect a no-fault status in the monitored circuit. At step **146** the program waits for the **waitFlag** to be cleared by an interrupt service routine, thus ending the fixed sample interval. When the **waitFlag** is cleared, the program returns to step **120** of the main loop.

[00027] FIG. 6 illustrates the **MeasureNegCycleState** routine entered at step **130**. This state is active for a selected number of loops, **fixedNumloopsA**, during which a check for a ground fault condition is made. This particular routine or determining a ground fault condition monitors the lowest voltage of a negative voltage cycle, and if it falls below a threshold value then a ground fault indication is declared. The **MeasureNegCycleState** routine begins by storing the input voltage in an array at step **153** for the next execution of the **MeasureN2GndState** routine. The loop number is incremented at step **154**. At step **156** the last peak voltage is compared to the current input voltage, and if the latter is greater, the value of the peak voltage is replaced by the lower voltage at step **158**. At step **160** the peak voltage is compared to a ground-fault HIGH threshold value, stored in the built-in memory of the microcontroller **10**. If the peak voltage is less than the ground-fault HIGH threshold value, the ground fault indicator is set at step **162**. Step **164** determines whether the number of loops so far is greater than **fixedNumloopsA**. If the answer is negative, the program returns to the main loop at step **137**. If the answer at step **164** is affirmative, then **nextState** is set to **WaitForZeroPlusState** at step **166**, and step **168** determines whether the peak voltage is greater than a ground-fault LOW threshold value. An affirmative answer at step **168** indicates that a ground-fault condition is not present in the monitored circuit and the program returns to the main loop at step **137**.

[00028] FIG. 7 illustrates the **WaitForZeroPlusState** routine entered at step **132**. The function of the **WaitForZeroPlusState** is to set up a circuit oscillation or ringing which provides the basis for detecting a neutral-to-ground fault condition in the monitored circuit. First, the **WaitForZeroPlusState** waits to detect a voltage which is zero or greater, and then

produces a ping output from the microcontroller **10**. This ping is supplied to the sensor **11** by the microcontroller **10** causing the resonant circuit to oscillate at its resonant frequency in a decaying fashion for a short period of time during which the neutral-to-ground test is conducted by the microcontroller **10**. At step **182** the counters are cleared. Step **184** determines whether the input voltage from the sensor **11** is equal to or greater than zero and, if the answer is negative, then the **WaitForZeroPlusState** state is maintained at step **185** and the program returns to the main loop at step **137**. If the answer at step **184** is affirmative, indicating that the voltage from the sensor **11** is zero or greater, then control is passed to step **186**. At step **186** a short pulse or ping is applied to the resonant circuit in the sensor **11**. Then step **188** changes **nextState** to **MeasureN2GndState**, and the program returns to the main loop at step **137**.

[00029]   FIG. 8 illustrates the **MeasureN2GndState** routine that is entered at step **134**. It is to be understood that the steps shown in Figure 8 are representative of those required for method 8, as described above, and that other methods for determining a neutral-to-ground fault condition could require different steps. This state performs a neutral-to-ground test by monitoring the rate of decay of the oscillation induced in the sensor circuit by the ping signal mentioned above. Specifically, the number of half cycles of this oscillation (humps), over a preselected threshold are counted during a predetermined fixed time period, **fixedNumloopsB**. The rate of decay in the amplitude of the oscillations will be faster when damping is present, and a rate of decay in excess of a preselected neutral-to-ground value threshold indicates a neutral-to-ground fault condition in the monitored circuit. At step **191** a sample is computed by adding the present input voltage to a corresponding input voltage sampled in the previous negative ½ cycle previously stored at step **153** of the **MeasureNegCycleState** routine. Then step **192** determines whether the resulting value is greater than a preselected hump detected HIGH threshold value and whether this hump has already been counted. If the answer at step **192** is affirmative, control is passed to step **193** to indicate that a hump has been detected, to set a hump detection indicator to TRUE, and to increment the number of detected humps by one at step **194**. If the answer at step **192** is negative, control is passed to step **196** to determine whether the magnitude of the voltage sample is less than a preselected no-hump detection LOW threshold value. If the answer at step **196** is negative, the hump detection indicator is set to FALSE, and control is passed to step **198** where the number-of-loops counter is incremented, and then to step **200**. At step **200** a check is made to determine whether the predetermined fixed time period, **fixedNumloopsB**, has expired. If the answer at step **200** is negative, control is passed back to the main loop at step **137**. If the answer at step **200** is affirmative, indicating that

fixedNumloopsB has expired, control is passed to step **202** where **nextState** is set to **WaitForZeroMinusState**. From step **202**, control is passed to steps **204** and **206** to check the number of humps detected. Step **204** determines whether the number of humps counted is greater than a preselected no neutral-to-ground HIGH limit threshold, and if the answer is affirmative, the neutral-to-ground fault indicator is set to FALSE (0) and control is passed to the main loop at step **137**. If the answer at step **204** is negative, step **206** compares the number of humps counted to a preselected neutral-to-ground LOW limit threshold value. If the number of humps is less than the neutral-to-ground LOW limit threshold value, the presence of a neutral-to-ground fault in the monitored circuit is suspected and thus the neutral-to-ground fault indicator is set to TRUE (1), and control is returned to the main loop at step **137**.

[00030]   FIG. 9 illustrates the **WaitForZeroMinusState** routine entered at step **136** following the neutral-to-ground test to synchronize and reset all the loop counters. At step **212** the peak voltage and the number-of-loops counter are set to zero. Step **214** then determines whether the input voltage is less than or equal to zero. If the answer at step **214** is affirmative, the **nextState** is set in step **218** to **MeasureNegCycleState**, and control is returned to the main loop at step **137**. If the answer at step **214** is negative, **nextState** is set or maintained as the **WaitForZeroMinusState**, and control is passed to the main loop at step **137**.

[00031]   In one embodiment, the microcontroller **10** is programmed to detect grounded-neutral conditions by using the sensor output signal to estimate the impedance of the neutral-to-ground connection in the power distribution system. In another embodiment, the microcontroller **10** is programmed to compare the sensor output response with a reference value to determine whether a grounded-neutral condition has occurred.

[00032]   While particular embodiments and applications of the present invention have been illustrated and described, it is to be understood that the invention is not limited to the precise structures disclosed herein and that various modifications, changes, and variations may be apparent from the foregoing descriptions without departing from the spirit and scope of the invention as defined in the appended claims.